The static friction response of non-glabrous skin as a function of surface energy and environmental conditions

M. Klaassen¹, E.G. de Vries¹, M.A. Masen²,⁎

¹ University of Twente, The Netherlands
² Imperial College London, UK

A B S T R A C T

The (local) environmental conditions have a significant effect on the interaction between skin and products. Plasticisation of the stratum corneum occurs at high humidity, causing this layer to soften and change its surface free energy. In this work we study the effects of the micro-climate on the frictional behaviour of skin in contact with materials with varying wettability. Friction measurements are performed under a range of micro-climate conditions using four different materials with a smooth surface finish. All measurements are performed twice on a single subject in order to minimise variation in skin properties. Results show that materials with a higher wettability show a larger increase in friction coefficient when exposed to warm, moist conditions. The friction force is modelled using the skin micro-relief, the elastic properties of the different skin layers, the surface chemistry of both skin and counter surface, and the environment, as input parameters.

1. Introduction

The human skin continuously interacts with a wide variety of surfaces and products. The desired interaction varies as some products, such as pens and prosthetics, require grip or sticking to the skin whilst other products, including clothing and shavers require low frictional forces. The mechanical and surface properties of the skin and the interacting materials, including the elastic modulus, surface free energy and surface texture play an important role in how these products interact with the skin, but also the micro-climate or the environment is of key importance [1]. Well known examples include the stickiness of clothing in humid tropical climates and the triboelectric charging of skin on cold, arid days.

Both the humidity and temperature affect a variety of properties of the skin, including the moisture content of the stratum corneum, the transepidermal water loss and the mechanical properties. A moist environment causes plasticising of the stratum corneum, which results in softening of the skin, and therefore an increase of the real area of contact. Additionally, moisture in the air leads to an increase of the free water in the outermost skin layer [2,3], which changes the skin’s surface free energy as the free water is polar [4]. As a result, the interaction between skin and counter surface changes. This change in interaction will be influenced by the surface free energy of the counter surface, as the combination of both surfaces with their surface free energies determine how strong the interacting forces are.

The combined effects of an increased real area of contact and altered surface free energy make the environment one of the key parameters determining the frictional behaviour of skin. This work focuses on studying the effects of temperature and humidity on the frictional behaviour between skin and counter surfaces with varying surface free energies.

2. Method

Friction measurements were conducted on the volar forearm at a range of environmental conditions using an in-house built setup, as shown in Fig. 1 and described in more detail in [1]. The setup consists of an enclosure in which both the temperature [T] and the relative humidity [RH] can be adjusted independently. The enclosure houses a reciprocating tribometer that measures the normal and friction forces between the probe material and the skin.

2.1. Experimental setup

The enclosure allows for precise control of the temperature and humidity whilst being sufficiently large to enclose a body part such as the lower arm. An elastic seal ensures a tight interface between the arm and the climate chamber. The temperature inside the climate chamber can be adjusted from room temperature to 40 °C with an accuracy of 0.2 °C. The relative humidity can be controlled from 40% RH to 95%

http://dx.doi.org/10.1016/j.biotri.2017.05.004
Received 22 December 2016; Received in revised form 3 May 2017; Accepted 4 May 2017
Available online 28 May 2017
2352-5738/ © 2017 Elsevier Ltd. All rights reserved.
RH with an accuracy of 2% RH. A mechanical fan is used to create air flow, ensuring constant conditions in the enclosure.

Experiments were performed at four different environmental conditions:

- 25 °C and 40% relative humidity (RH), referred to as the ‘cold and dry’ environment,
- 25 °C and 90% RH, referred to as ‘cold and moist’,
- 37 °C and 40% RH, referred to as ‘warm and dry’, and
- 37 °C and 90% RH, referred to as ‘warm and moist’ conditions.

2.2. Probe materials

Four probes of different materials are used for the experiments to study the effect of surface free energy on the frictional behaviour: soda lime glass, silicon nitride, chrome steel and PTFE. Contact angle measurements are performed to calculate the polar and dispersive component of the surface free energy using the Owens and Wendt method. Confocal microscopy images are taken for measuring surface parameters. The properties of the probes are summarised in Table 1. Hendriks [5] and Derler [6] have shown that the roughness of the counter surface has a strong effect on the measured friction: for very rough surfaces the contact and friction behaviour is dominated by deformation or hysteresis effects, whilst for very smooth surfaces (Ra < 0.2 μm) the adhesive forces in the contact dominate the friction behaviour. In this study we employ a range of counter materials with surface roughness Ra in the range of 50 nm, which can be considered to be smooth and therefore we assume any variations in friction behaviour to be primarily caused by adhesion effects. PTFE is an interesting material to include in this study, because of its low surface free energy, but unfortunately this material could not be manufactured with the required smooth surface. As a result, the surface roughness of the PTFE specimens in this study was 0.18 μm. The above assumption of smooth surfaces and the effects of roughness will be discussed in more detail in Section 3.3.1.

2.3. Experimental procedure

2.3.1. Skin hydration

At the start of each experiment a measure for skin hydration (5 readings per measurement) is obtained using a Corneometer (Courage-Khazaka Electronic), after which the skin is acclimatised to the test environment, followed by the actual friction measurement. Following the friction measurement, the skin hydration was again measured. The obtained skin hydration results (96 ‘Before’ averaged readings, and 24 averaged readings per environment) are shown in Table 2, showing that a moist environment has a significant effect on the Corneometer readings.

2.3.2. Acclimatising and friction measurement

The forearm is placed into the enclosure and acclimatised during a period of 10 min. During acclimatising the test probe is not in contact with the skin. Following acclimatising, the probe is placed onto the arm and the sliding contact is initiated while the arm remains stationary. The probe makes two reciprocating sliding motions with a stroke of 30 mm at a speed of 0.2 mm/s. The total sliding distance for one measurement is 120 mm. The settings ensure that a full macroscopic sliding contact is achieved, with the speed a compromise between minimising any effects of viscoelastic energy loss and keeping the total duration of an experiment acceptable for the subjects. As shown previously [1] the friction between probe and volar forearm shows some running-in like behaviour, with a steady state friction force achieved after the first reciprocating motion. At each of the four environmental conditions, measurements were performed with the four materials at three normal loads of 0.2, 0.4 and 0.8 N. Each measurement was repeated twice, which totals 96 friction measurements. The measurements were randomised over environment, counter surface and normal load. Between each measurement there was a period of at least one hour.

<table>
<thead>
<tr>
<th>Material</th>
<th>Water contact angle Mean ± SEM</th>
<th>Total SFE γs = γs^p + γs^d [mJ/m^2]</th>
<th>Polar SFE γs^p [mJ/m^2]</th>
<th>Dispersive SFE γs^d [mJ/m^2]</th>
<th>Ra [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soda lime glass</td>
<td>29.5 ± 0.3</td>
<td>64.8</td>
<td>37.4</td>
<td>27.4</td>
<td>0.052</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>22.2 ± 0.1</td>
<td>68.2</td>
<td>41.3</td>
<td>26.9</td>
<td>0.036</td>
</tr>
<tr>
<td>Chrome steel</td>
<td>68.5 ± 1.3</td>
<td>39.9</td>
<td>12.6</td>
<td>27.4</td>
<td>0.036</td>
</tr>
<tr>
<td>PTFE</td>
<td>102.0 ± 1.2</td>
<td>17.8</td>
<td>2.1</td>
<td>15.8</td>
<td>0.172</td>
</tr>
</tbody>
</table>
2.3.3. Skin surface geometry

After the friction measurements, a polymer replica of the skin surface geometry was created using a replicating compound (CuDerm, Dallas, USA), enabling measurement of the surface geometry using confocal microscopy. A typical image is shown in Fig. 2.

For each environment condition, four skin replicas were made and measured. The results in Table 3 show the average roughness Ra. The surface texture of the skin in terms of roughness parameters seems to not be significantly affected by the environment.

2.3.4. Test person

The experiments are performed on a single healthy volunteer (Male, 29 y, Caucasian). The subject did not use any skin care products and no particular skin treatment was performed before the experiments. The experimental procedure and parameters are summarised in Table 4. The experiments were executed in a random order.

2.4. Signal processing

The normal and friction force signals are recorded at a sampling frequency of 100 Hz. The standard deviation of the noise in the normal direction was found to be 6 mN and 1 mN for the lateral direction.

A digital 1st order Butterworth low-pass filter of 2 Hz was applied to remove the noise. Signal drift was removed by subtracting a linear fit from the entire dataset of 10 min testing. The static coefficient of friction, $\mu_s$, is calculated by dividing the peak value of the friction force by the normal load. In this work we will only report the static friction forces, however the dynamic friction force, calculated from the mean friction force in the centre of the sliding stroke, was found to be typically about 84% of the static friction force. As explained before, all values reported in this work concern those measured during the second (i.e. final) friction cycle and are the average of two separate measurements done at different times. The reported error bars in the graphs show the total range (minimum and maximum) of the measured friction forces for each condition.

2.5. Direction dependence of the measured friction force

The friction measurements are done on the volar forearm. Initially the probe moves 30 mm in the distal direction (i.e. towards the wrist), this is followed by a returning proximal motion (i.e. towards the elbow). Three typical friction force signals were observed, as shown in Fig. 3. These graphs show markedly different behaviour depending on

---

**Table 2**

Skin hydration before and after exposed to alternate climate.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Corneometer readings (Mean ± Standard Error) [AU]</th>
<th>Significant difference from 'Before' ($\alpha = 0.05$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Before'</td>
<td>34.8 ± 0.5</td>
<td>–</td>
</tr>
<tr>
<td>25 °C 40%RH</td>
<td>31.7 ± 0.5</td>
<td>No</td>
</tr>
<tr>
<td>25 °C 90%RH</td>
<td>47.7 ± 0.8</td>
<td>Yes</td>
</tr>
<tr>
<td>37 °C 40%RH</td>
<td>32.5 ± 0.5</td>
<td>No</td>
</tr>
<tr>
<td>37 °C 90%RH</td>
<td>82.8 ± 2.1</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Table 3**

Surface parameters at different environments.

<table>
<thead>
<tr>
<th>Climate</th>
<th>$R_a$ [(\mu m)] (mean ± standard error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 °C, 40% RH</td>
<td>18.7 ± 0.2</td>
</tr>
<tr>
<td>25 °C, 90% RH</td>
<td>18.1 ± 0.7</td>
</tr>
<tr>
<td>37 °C, 40% RH</td>
<td>19.3 ± 0.6</td>
</tr>
<tr>
<td>37 °C, 90% RH</td>
<td>19.9 ± 0.6</td>
</tr>
</tbody>
</table>

**Table 4**

Summary of experimental parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>25 °C and 37 °C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>40% and 90%,</td>
</tr>
<tr>
<td>Total number of measurements</td>
<td>96</td>
</tr>
<tr>
<td>Acclimatising time for skin to environment</td>
<td>600 s</td>
</tr>
<tr>
<td>Total lateral stroke</td>
<td>30 mm, (2 reciprocating motions)</td>
</tr>
<tr>
<td>Probe velocity</td>
<td>0.2 mm/s</td>
</tr>
<tr>
<td>Total duration of a single measurement</td>
<td>20 min (10 min acclimatising, 10 min friction measurement)</td>
</tr>
<tr>
<td>Normal load</td>
<td>0.2 N, 0.4 N, 0.8 N, each performed twice</td>
</tr>
<tr>
<td>Probe material</td>
<td>Chrome steel, glass, silicon nitride and PTFE balls with a diameter of 30 mm</td>
</tr>
<tr>
<td>Test person</td>
<td>One subject, Male, 29 y, Caucasian</td>
</tr>
<tr>
<td>Skin treatment</td>
<td>None</td>
</tr>
</tbody>
</table>
3. Results & discussion

3.1. Hysteresis loops

Fig. 4 shows four typical friction hysteresis loops as measured at a normal load of 0.2 N using the glass specimen. Each colour shows the friction force at a different micro-climate, with blue tones representing "cold", red representing "warm", light colours representing "dry" and dark colours representing "moist" conditions. Similar graphs are obtained for the higher normal loads and the other materials. On the horizontal axis the probe position is shown, the initial position is closest to the elbow. The specimen slides 30 mm towards the wrist, followed by a return to the initial position. The friction force is shown on the vertical axis.

The friction force increases up to the point where full sliding occurs. The four curves clearly show the effect of the environment on the friction behaviour. The lowest friction force is observed at the dry and cold environment (turquoise line), while the highest friction force is obtained at the warm and moist climate (red). Furthermore, the cold and moist environment (blue) shows a higher friction force than the warm and dry environment (orange).

3.2. Friction force as function of the normal load for different conditions

Fig. 5 shows the mean peak static friction force measured for each material and environmental condition at 0.2, 0.4, and 0.8 N normal load. Clearly the friction force increases with increasing normal load. Generally, the spread in friction force values (minimum and maximum value are shown as error bars) are larger for the higher normal loads and smaller for the lower normal loads.

For each material the cold and dry environment gives the lowest friction coefficients. The warm and dry environment results in lower frictional forces than the cold and moist environment. No clear difference was observed between the cold and moist environment and the warm and moist environment.

3.3. Effect of the environment on the frictional behaviour of skin in contact with the different materials

From the above, it is clear that the environment has a major effect on the friction between a sliding probe and the skin. Fig. 6 shows the percentage increase of the coefficient of friction when the environment is changed. The cold and dry environment is taken as the base value (i.e. 100) for each of the materials. The largest increase in coefficient of friction is observed for the PTFE sample in a warm and moist environment. This result is not as expected, as the hydrophobic nature of PTFE would prevent capillary forces in the contact that increase the adhesion between the two surfaces.

The capillary forces between the surfaces depend on the water contact angles of both materials in contact. Uptake of moisture by the stratum corneum will decrease the water contact angle and therefore increase the surface attraction. The contact between a hydrophobic material such as PTFE and skin results in a positive (i.e. repulsive) capillary force, thus decreasing the real area of contact, whilst moisture makes the skin surface more polar, but as PTFE is a non-polar material, this would also not explain the large increase in friction observed. As a result, the large increase in friction is hypothesised to be due to the roughness of the PTFE sample, which was approximately four times rougher than the other samples, in combination with the reduced elastic modulus of the stratum corneum in warm, moist conditions. This was also confirmed using an even more rough PTFE sample with a roughness of Ra = 0.4 μm, which gave lower friction forces in the cold and dry environment (± 0.04 N) and higher values (1.43 N) at the warm and moist conditions.

3.3.1. Increasing temperature

When the effect of the temperature is analysed, the largest increase is obtained for the silicon nitride sample, followed by glass, chrome steel, and PTFE. This ranking is the same as the ranking for the contact angles with water for these materials. The lower water contact angle (more hydrophilic) results in a larger negative capillary pressure which
increases the adhesion between the two surfaces. Furthermore, when the temperature is raised the transepidermal water loss (TEWL) of the skin increases [8]. At 40% relative humidity, water easily evaporates into the surrounding air, however, a counter surface with a hydrophilic nature will be covered with a water film which will result in the formation of capillary bridges and/or plasticisation of the stratum corneum, which both increase the friction force.

3.3.2. Increasing humidity

At increased humidity the friction forces increase strongly. The increase is less strong for the glass sample than for the other three samples. A possible reason for this result is the rapidly changing moisture content in the stratum corneum at high relative humidities. The moisture content of skin is about 10% at a humidity of 50% RH [9,10], 30% at a humidity of 90% and the skin contains 70% moisture at 100% RH or when immersed in water. The rapid change in moisture content will result in relatively large variations in the skin surface chemistry and thus affect the friction behaviour.

3.3.3. Increasing both temperature and humidity

The largest increase of the coefficient of friction is found for the combined warm and moist condition. Plasticisation of the skin occurs as
the result of the combination of a relatively large amount of available water in the surrounding air, the high humidity that limits evaporation of water from the skin as well as the increase in TEWL. Additionally, capillary forces will increase the adhesion in the contact.

3.3.4. Absolute humidity

Martin used NIR spectroscopy to show a linear increase in both the free and bound water content in the stratum corneum with increasing absolute humidity $\chi$ [11]. The absolute humidity shows how much water is present in the surrounding air and thus is available to interact with the skin, and can be calculated from the relative humidity and the temperature following [12]:

$$\chi = k(T + d)^{-1}(D + d)^a 10^{b/\sqrt{d}}$$

Where $a$, $b$, $c$, $d$, and $k$ are constants (see [12] for values), $T$ the temperature in degrees Celsius and $D$ the dewpoint temperature (°C). The dewpoint can be calculated from:

$$RH = (T + d)^{-a}(D + d)^b 10^{c/\sqrt{d}}$$

For all tested materials an increasing trend of friction force is observed with increasing absolute humidity. The warm and dry environment represents an absolute humidity of approximately 18 g/m$^3$ whilst the cold and wet environment represents an absolute humidity of approximately 21 g/m$^3$. Despite the relatively small difference in absolute humidity, the differences in friction coefficient between these two environments are significant, indicating that the absolute humidity is not the only parameter determining the frictional behaviour. As an example, the relative humidity will determine diffusion processes such as evaporation of water from the skin into the surrounding environment while the absolute humidity has an effect on the plasticisation of the skin.

3.3.5. Relationship between adhesion and static friction

The static friction force is proportional to the real area of contact ($A_{\text{real}}$) and the shear strength of the interface $\tau$.

$$F_{j} = \tau \cdot A_{\text{real}}$$

Van Kuilenburg developed a model for the real area of contact between a spherical indenter and the volar forearm, by taking into account the length scale effect on the effective elastic modulus, the skin microrelief and the adhesion between skin and counter surface [13,14]. The real area of contact can be described as:

$$A_{\text{real}} = K_{1}E^{\frac{1}{4}}(1 + \frac{\pi^{2} + 1}{2})$$

Here, $a$, $b$ and $K_{1}$ are calculated from the effective elastic modulus at the different length scales, whilst $K_{1}$ is also a function of the skin microrelief. The applied load $F$ in this equation is calculated following the JKR model.

$$F_{\text{app}} = F + 2\cdot F_{\text{adh}} + 2\cdot \sqrt{F_{\text{adh}}\cdot (F + F_{\text{adh}})}$$

In which:

$$F_{\text{adh}} = \frac{3}{2} \pi R W_{12}$$

The work of adhesion $W_{12}$ can be determined using the polar and dispersive components of the surface free energy, following from the Owens and Wendt model [15,16].

Fig. 7. Interfacial shear strength.
The polar and dispersive component of the various materials has been calculated above, in 2.2. The surface free energy of human skin is strongly dependent on the environment [4,17,18]. Kenney found that the dispersive component remained unchanged at a value of 32–35 mJ/m² and the polar component increased from 5 to 22 mJ/m² when the humidity and temperature were increased from 34% RH and 23 °C to 60% RH and 33 °C respectively. Assuming a linear increase of the polar component with absolute humidity, the work of adhesion can be calculated for the various combinations at the different environments.

As Kuilenburg's contact model does not include the effects of the environment, we employ model of Butt for the effect of humidity on the adhesion and the real area of contact between a sphere and flat surface [19]. This model was developed for soft materials, which means it can be applied to the individual skin microrelief features. The capillary force in a single asperity contact is given by:

$$ F_c = -\pi R_i^3 \frac{\gamma}{r} \sin^2 \beta $$

with $R_i$ as the equivalent radius of the skin microrelief features [14], $r$ the Kelvin length, which includes effects of the relative humidity and temperature, and $\beta$ the filling angle. The model assumes impermeable surfaces, meaning that effects following from water loss from the skin are not included.

The filling angle is calculated using the Young–Laplace and Kelvin equations, along with the geometrical analysis of the contact. The capillary force contributes to additional deformation in the contact area. The total adhesive force is used to calculate the additional contact area following the JKR contact model.

Using the combined models of Kuilenburg and Butt, the real contact area for each experiment can be calculated, allowing for the calculation of the interfacial shear strength $\tau$. Fig. 7 shows the interfacial shear for each experimental condition as a function of the absolute humidity. Carpick observed a relationship between the surface energy of the materials in contact and the interfacial shear strength ($\tau \propto \gamma^{0.44}$) [20], however this was not observed in our measurements as the interfacial shear strength does not show a clear trend for any of the normal loads and materials applied. The interfacial shear strength ranges from 8 kPa for the cold and dry environment to 30 kPa (ignoring the PTFE sample) for the warm and moist environment. These values are in the same order of magnitude as values reported by Derler and Adams [3,6]. The interfacial shear strength of the skin – PTFE interface in a warm and moist environment is considerably higher than that of the other materials. However, as discussed before in Section 3.3, rather than an effect of the interfacial shear strength this has been attributed to the growth in real area of contact due to the roughness of the PTFE specimen.

By assuming that the interfacial shear strength linearly depends on only the absolute humidity (excluding the PTFE specimen), it is possible to calculate the friction force using the mechanical properties of skin, the surface geometry of skin, the environment and the surface chemistry properties of both surfaces, as input parameters. Fig. 8 shows the calculated friction force plotted against the actually measured friction force. The dotted line indicates perfect agreement between experiments and model.

Although there is considerable spread of the data points around the line of perfect agreement between model and measured data, modelling the friction using a climate-affected interfacial shear strength appears to describe the friction forces fairly well, particularly at the lower end of the graph. The larger differences in friction forces at higher loads might be related to the effects of surface roughness of the specimens. The used specimens were assumed perfectly smooth, but minor differences in surface micro-geometry will result in a different growth of real contact area with increasing load, which will be more pronounced with a relatively soft upper skin layer.
4. Conclusion

The frictional response of human skin is highly dependent of the environmental condition. Experiments using four materials, covering a large range of surface free energies, executed at a range of normal loads and environmental conditions show a strong increase of friction coefficient with both temperature and humidity. Softening of the stratum corneum and the formation of capillary forces are hypothesised as the main drivers behind this increase. Capillary forces develop as a result of the water vapour present in the air as well as water that is released from the skin.

The shear strength of the interface between specimens and the human skin can be calculated from the measured coefficient of friction and the calculated real area of contact area between the contacting bodies. When this real area of contact is quantified using a model that incorporates surface free energy, adhesion and the effects of humidity, it appears the interfacial shear strength is mainly affected by environmental conditions, whilst material properties and loads are of secondary importance.

Acknowledgements

This research is supported under grant number 12673 by the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs.

References